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SIMULATION STUDY OF VISTA/F-16 MANEUVERABILITY ENHANCEMENT USING FOREBODY VORTEX CONTROL

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ABSTRACT

A piloted experimental study of potential enhanced task performance resulting from improved high angle-of-attack aerodynamic and flight control capability was conducted in the Air Force Research Laboratory's engineering flight simulator facility. The simulation database used was representative of the aerodynamics and inertias of the Variable-stability In-flight Simulator Test Aircraft (VISTA) / F-16. The VISTA variable-stability control laws were not used. Three flight test pilots evaluated both baseline and three modified versions of the simulated aircraft using a variety of high angle-of-attack tasks. Aerodynamic modifications were based on wind tunnel data from a previous effort which examined various means of extending the aircraft angle-of-attack limits. These focused primarily on the lateral-directional characteristics in the twenty-nine to thirty-seven degree range. Flight control modifications came from a new approach to control of lateral-directional dynamics which used variable structure control and describing functions. This controlled the forebody vortices to achieve improved roll coordination. This paper presents the results of analyzing the entire set of experimental output data for the effects of the configuration changes on high angle-of-attack maneuverability and departure resistance. The results show that use of the modifications greatly increases departure resistance and provides significant improvement in roll maneuverability for flight up to the maximum lift angle of attack.

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INTRODUCTION

The USAF Research Laboratory's Control Dynamics Branch has been involved in high angle-of-attack (AOA) flight research for the last several years in the areas of aircraft dynamics, aerodynamics and flight control. [6] describes a piloted simulation study of a configuration that represents the culmination of two earlier efforts[2,3] involving modeling and non-realtime simulation of aerodynamic and related flight control law modifications to a model of the baseline VISTA/F-16. Only part of the large volume of piloted simulation output data had been analyzed for inclusion of results in [6]. A complete analysis of the data has now been done and this paper presents the results, specifically focusing on the effects of the modifications on the VISTA's departure resistance and maneuverability at high-AOA (i.e. above the 29 degree AOA-limiter and up to the maximum lift AOA at 35 degrees). This introductory section briefly reviews the critical technical background concerning the modified aerodynamics, associated new control laws and the design and conduct of the piloted experiment from which the results described below were obtained.

<u>Aerodynamic Modifications</u> [2] describes a wind-tunnel test program conducted in 1991-2 to define the aerodynamics of an F-16 with the following aerodynamic modifications: (i) cut-back wing leading-edge extension (LEX), (ii) forebody chines and (iii) pneumatic forebody vortex control as shown in Figure 1. These will be referred to as the LEX/Chines/Blowing(LCB) modifications, with the blowing being an active control effector.

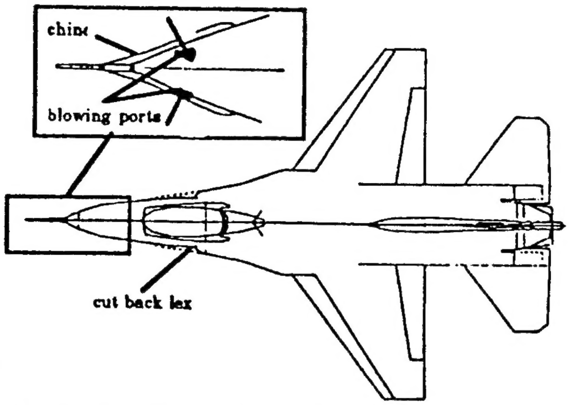

Figure 1 Active and Passive Modifications

The high-AOA effects sought were: (i) improved directional stability (due to the chines), (ii) improved longitudinal stability and elimination of the high-AOA pitch trim point (due to a cut-back LEX), and (iii) increased directional control power (due to forebody vortex control). The specific beneficial changes to the total pitching, rolling and yawing moments due to the passive (i.e., no active vortex control) modifications as well as the rolling and yawing moments resulting from the active vortex control are shown in figures 2 through 6 in [6]. In turn, these changes affect the F-16's flight characteristics as follows: (i) the F-16 tendency towards hung stall in the vicinity of sixty degrees AOA is eliminated by the effective nosedown pitching moment increment produced by reduction of the LEX area forward of the center of gravity, (ii) the increase in yawing moment above twenty-degrees AOA generated by the chines reduces the directional instability, (iii) Cut-back LEX and chines together result in an improved rolling moment for AOA greater than thirty degrees, (iv) the vortex control generates additional yawing moment, (v) the vortex control generates an associated incremental rolling moment, which is predictable and proverse through approximately thirty-five degrees AOA - however, it is adverse above thirty-five degrees and this is noted in [3] as the limiting factor in the control of sideslip.

<u>Control Law Implementation</u> [3] describes the development of control laws for a forebody vortex control system that augments yaw control power as the rudder loses effectiveness at high AOA. Figure 2 shows the control law block diagram from that report. The approach used in [3] was to modify the existing F-16 control laws by adding an outer feedback loop for the forebody vortex control. The outer loop control law was bang-bang with three possible states: full blowing from the left forebody slot, full blowing from the right forebody slot and no blowing. The bang-bang control law was chosen because it was considered to be the most conservative. The authors of [3] had no data that suggested linear actuation was possible and the bang-bang control law evolved naturally from the bang-bang actuator. Design of the system was accomplished using variable structure control and describing functions and is described in detail in [3]. Reference 3 also gives a detailed summary of the non-realtime simulation study of potential high-AOA flight stability and performance enhancements.

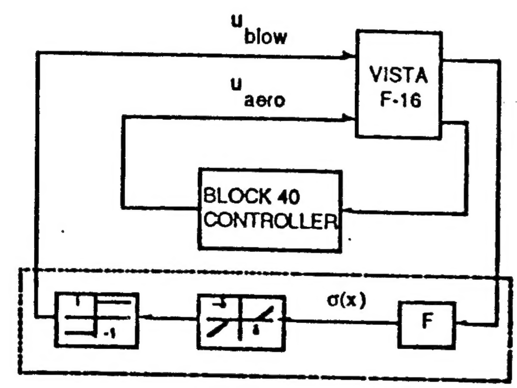

Figure 2 Forebody Blowing Control System

Just as the wind tunnel tests of [2] validated the predicted improvements in directional stability and directional control power, the results in [3] showed that use of the modifications allow the extension of the VISTA/F-16's AOA envelope to 37 degrees AOA. The same non-realtime simulation used in [3] was used in the piloted simulation study conducted in mid-September 1995 and described in detail in [6].

<u>Aircraft Configurations</u> The piloted study used four distinct configurations:

Baseline(BASE) = baseline VISTA (29 degree AOA limiter)

Extended(EXT) = baseline configuration with limiter extended to 40 degrees

LEX/Chines(LC) = Extended configuration with cutback LEX and chines

LEX/Chines/Blowing(LCB) = LC configuration with active vortex blowing controller

EXT, LC, and LCB are the same configurations used in [3].

Pilots The pilots used for the experiment were highly qualified veteran F-16 flight test pilots assigned to the Air Force Flight Test Center at Edwards AFB and Wright-Patterson's F-22 SPO. This was considered important both for their ability to perform the experiment as designed and for their ability to comment on the results with respect to application of the enhanced capability to operational use.

Tasks The tasks required of the pilots during the study were divided into performance, flying qualities and target acquisition evaluation tasks. Tasks 1 through 3 are the same as the unmanned simulation tasks used in [3] and were repeated to provide a direct comparison to those earlier results. Task 1 defines the maximum roll rate at a given AOA for the test speed. Task 2 adds a roll attitude capture to task 1. Task 3 extends the speed range for the roll and capture dynamics as well as adding coupling dynamics from the initial angular motions. Roll acceleration and rate are the primary quantities of interest in these tests, along with the pilot assessment of the flying characteristics. Tasks 4 and 5, which are taken from the Standard Evaluation Maneuvers of [5], introduce varying degrees of difficulty to the task. This is done to examine the effect of aircraft capability on time to acquire a benignly maneuvering target. Initial conditions were chosen to assure the ability to perform the maneuvers with the AOAs of interest and in such a way as to make the task operationally relevant. The time to acquire and the maximum roll rate and acceleration are the main quantitative interest, with pilot ratings and commentary again gathered as the qualitative data. The tasks are described below.

Performance:

Task1 (Max Lateral Stick Response): From a trimmed condition, the pilot aggressively pitched the aircraft up to the desired AOA and applied a two-second full right lateral stick pulse while holding the test AOA.

Flying qualities evaluation:

Task2 (Split-S): From a trimmed condition, the pilot pitched the aircraft up to the desired test AOA (AOAt). He then rolled 180 degrees while maintaining AOA. He continued to pull through to achieve a 180 degree heading change.

Task3 (Loaded Roll Reversal): The pilot entered a 2-g right turn. He then pitched up to the desired test AOA. He then applied a left lateral stick pulse to capture approximately -60 degrees bank angle while holding the test AOA.

Target acquisition:

Target set-up: One pilot flew the baseline configuration from 1-g level trim into a constant AOA 3-g descending turn. The results were recorded and used as the target aircraft for tasks 4 and 5.

Task4 (Gross Lateral Acquisition): The test aircraft began in 1-g level flight approximately 1500 feet behind and 1000 feet below the target aircraft. When the target rolled, the pilot hesitated until the target was approximately 10 to 20 degrees off of the nose. He then quickly pulled to the test AOA, hesitated momentarily, then rolled aggressively while holding AOA to capture the target.

Task5 (Gross Longitudinal Acquisition): The test aircraft began in 1-g level flight approximately 3000 feet directly behind the target aircraft. The pilot allowed the target to reach a predetermined angle off the nose, then rolled to get into the target's maneuver plane. He then hesitated until he was in a lag position such that the test AOA occurred at target capture.

Flight Conditions The tasks mentioned above were performed for a range of trim conditions from [3] with Mach numbers between 0.3 and 0.7 and altitudes between 10,000 ft and 25,000 ft.The test AOAs ranged from 20 to 35 degrees.The combination of flight condition (Mach and altitude at trim condition) together with the desired AOAt to which the pilot was to pull define what is referred to as a case in the discussion below.

Case Definitions The 189 simulation runs done by the pilots (63 runs x 3 pilots) were organized into cases, defined in Table 1 :

Case	Task	Mach	Alt	AOAt	Configurations
1	1	.3	10k	30	EXT,LC,LCB
2	1	.3	10k	35	EXT,LC,LCB
3	2	.3	10k	30	EXT,LC,LCB
4	2	.3	10k	35	EXT,LC,LCB
5	2	.5	10k	30	EXT,LC,LCB
6	2	.5	10k	35	EXT,LC,LCB
7	2	.7	10k	30	EXT,LC,LCB
8	3	.6	25k	20	BASE,EXT,LC,LCB
9	3	.5	25k	25	BASE,EXT,LC,LCB
10	3	.5	25k	30	EXT,LC,LCB
11	3	.4	25k	35	EXT,LC,LCB
12	4	.4	24k	20	BASE,EXT,LC,LCB
13	4	.5	24k	25	BASE,EXT,LC,LCB
14	4	.5	24k	30	EXT,LC,LCB
15	4	.5	24k	35	EXT,LC,LCB
16	5	.6	25k	20	BASE,EXT,LC,LCB
17	5	.5	25k	25	BASE,EXT,LC,LCB
18	5	.5	25k	30	EXT,LC,LCB
19	5	.5	25k	35	EXT,LC,LCB

Table 1 Definition of Experiment Cases

In the conduct of the experiment the order of the configuration was randomized. Pilots were only told before starting the task whether they would be flying a configuration with a raised limiter - but not which of the three raised limiter configurations it was.

SIMULATION STUDY RESULTS

In this section results of the piloted simulation study are presented which show the beneficial effects that the modifications have on both departure resistance and maneuverability at high angles of attack. The results presented here were obtained primarily by automated simulation output data processing and analysis.Pilot commentary was recorded on audio tapes for the entire experiment. Commentary on these tapes is very consistent with the analytical results presented here.

Departure Resistance The primary objective of both the non-realtime simulation study done in [3] and this study was to determine the feasibility of expanding the VISTA/F-16's AOA envelope and thus increasing the range of AOA that it might simulate. The key to succesfully accomplishing this expansion is to enhance the vehicle's departure resistance up through the unstable 30 - 35 degree AOA region. Table 2 summarizes the occurences of departures. A departure is defined as a simulation run which contains an AOA greater than 75 degrees or a sideslip greater than 20 degrees. All departures encountered were for runs involving the EXT configuration, and all of these contained AOAs that were above 75 degrees. The highest sideslip value obtained in the study was approximately 13 degrees. As the table indicates, Task 2 accounted for all but 1 of the 10 departures(out of 189 simulation runs), with a very uniform split across pilots and Task 2 cases noted. Similarly, Table 3 summarizes the percentage of departure occurences for the entire simulation study, based on aircraft configuration. As is clearly evident, the modifications do allow the VISTA to fly to maximum lift AOA with definite increased departure resistance.

Pilot1	Pilot2	Pilot3
Task2/Case3	Task2/Case4	Task2/Case3
Task2/Case5	Task2/Case6	Task2/Case4
Task2/Case6	Task2/Case7	Task2/Case5
Task3/Case11		

Table 2 Departure Occurence cases

Config	Number of Runs	Departures	Percent
BASE	18	0	0
EXT	57	10	18
LC	57	0	0
LCB	57	0	0

Table 3 Percentage of Departures by Configuration

Maneuverability In addition to departure resistance, this study addressed the issue of whether the modifications would yield greater maneuverability of the aircraft. Note that no single uniformly accepted definition of maneuverability is in use across the aerospace community. Furthermore, it is important to realize that any such definition of maneuverability would differ still from the concept and definition of tactical utility. One approach, which is task dependent, taken towards quantifying maneuverability changes observed due to the modifications was to estimate the time it took the pilots to capture either a real target or some "target" state. This was the approach taken in [6]. Note that the results concerning maneuverability based on capture time and the PM metric described in [6] only represent a small portion of the 189 simulation runs performed during the experiment. The authors found that the graphical analysis needed for this approach (see Figures 8 and 9 of [6]) could not be readily automated, and was thus very tedious and time consuming.

The results shown there (Figures 10-16) are fairly inconclusive.

For this paper, a second approach to the quantification of maneuverability was used. This approach was used for the entire experimental matrix (all 189 simulation runs). Although perhaps not as close to the concept of tactical utility as the capture time approach, it has the advantage of being readily amenable to automation, while still having an obvious correlation with possible improvements in the vehicle's tactical utility. The second approach to defining maneuverability was to relate it to the achievement of optimal values of certain critical aircraft state parameters. These parameters were:

1) Stability axis roll rate, given by $P_s = P_b \cos\alpha + R_b \sin\alpha$ where P_s = stability axis roll rate, P_b = body axis roll rate, R_b = body axis yaw rate, α = angle-of-attack

2) Stability axis roll acceleration

3) Loaded body axis roll rate, given by $P_{bL} = (P_b \; n_z \; g)/\cos\alpha$ where P_{bL} = loaded body axis roll rate, n_z = load factor, g = gravitational acceleration

4) Sideslip

5) Pitch rate

6) Pitch acceleration

These are referred to as maneuverability parameters. Although sideslip is not typically classified as a maneuverability parameter, it is included in the group because (as the results will presently show) it is highly correlated with lateral maneuverability, as measured by the first three corresponding maneuverability metrics defined below:

1) Maximum stability axis roll rate attained during a simulation run

2) Maximum stability axis roll acceleration attained during a simulation run

3) Maximum loaded body axis roll rate attained during a simulation run

4) Maximum sideslip angle attained during a simulation run

5) Maximum pitch rate attained during a simulation run

6) Maximum pitch acceleration attained during a simulation run

These 6 maneuverability metrics were calculated for the entire experimental design matrix. Figures 3 through 10 contain plots summarizing the results.

The analysis done and plots generated form a systematic attempt to show the effects of these modifications on the 6 maneuverability metrics defined above. Although both individual pilot results and pilot-averaged results and plots were obtained, for conciseness only the pilot-averaged plots are displayed here. Since individual pilot differences were noted during the execution of similarly defined tasks, the pilot-averaged results are assumed to be the best estimate of the effects that the modifications had on the maneuverability metrics. Likewise, results were tabulated for maneuverability both accounting and not accounting for departures. If any pilot departed on a case's run, the pilot averaged result was considered to be a departure. For the metrics chosen, the expected trends were that metrics 1-3 would increase for a configuration change from EXT to LC and from LC to LCB. Metric 4(maximium sideslip attained during the run) would decrease, due to the chines and blowing, with this causing the improved roll predicted to be seen in metrics 1-3. Since the cutback LEX was intended to decrease pitch up tendency, a slight decrease in pitch rate and acceleration was expected in LC and LCB compared to BASE and EXT.

Maneuverability Metric Results (Pilot-avg Summary Plots): The plots shown in figures 3 through 8 summarize pilot-averaged results for all configurations, all 19 cases and each of the 6 maneuverability metrics.Circled markers indicate departures. Based on the metric definitions, it is intuitively clear that for metrics other than metric 4, the more often the LC and LCB values are highest on the plot, the more that indicates enhanced maneuverability attributed to the modifications. A close scanning of these plots indicates that the modifications definitely tend to yield more case results with higher roll rates and

accelerations and lower max sideslip values. But the EXT configuration has a predominance of highest pitch rate and acceleration values. However, as expected , there were several departures for the EXT configuration. Likewise, as noted above, the cutback LEX would be expected to produce less pitch up.

Maneuverability Metric Results(Configuration Comparisons Not Accounting For Departures): Here a simple tabulation was done to see how many times each configuration got the best value for the various 19 cases. Here "best" means highest , except for metric 4 (maximium sideslip attained during the simulation run). Departure was not considered in the tabulation. For the pilot-averaged plots shown in Figures 3 through 8 and the 6 maneuverability metrics, respectively, Figure 9 indicates the percentage of cases for which each configuration had the best value. Thus, for example, the LCB configuration obtained the best value of metric 1(maximum stability axis roll rate attained during the run) for more than 50 percent of the 19 cases. Likewise, the LCB configuration obtained the best (lowest) value of metric 4 for more than 60 percent of the 19 cases. The EXT configuration obtained the best value for metrics 3,5 and 6 for the highest percentage of the cases. However, the results shown in Figure 9 were obtained not Accounting For Departures(AFD).

Maneuverability Metric Results(Configuration Comparisons AFD): In Figure 10 departures are accounted for by simply defining the second-best value obtained as the best if the best value was for a departed run. Here the modified configurations LC and LCB obtain considerably higher percentages of best values for the pitch maneuverability metrics relative to the EXT. Indeed, as Figure 10 shows, if only non-departed simulation run values are allowed to be considered best , then the LC and especially the LCB configuration shows striking predominance in the percentage of cases for which it received the best value for ALL maneuverability metrics(only tieing with the BASE configuration for most bests in pitch acceleration).

Figure 10 shows that roll maneuverability is enhanced, sideslip attenuation is enhanced and pitch maneuverability is certainly not degraded by making the LC and LCB modifications. Table 3 below gives the amount of enhancement in the VISTA's high-AOA maneuverability produced by the modifications.

Amount of maneuverability enhancement produced by modifications: To arrive at these estimates, only the pilot-averaged results for non-departed runs were used, since a "bottom-line" estimate of enhancement should not consider departures as contributing to enhancement. Since Figure 10 shows that for non-departed runs, the LCB configuration was best for all metrics the majority of the time (only tieing with the BASE configuration for most bests in pitch acceleration), the numbers in Table 4.3 are obtained by averaging the percentage of enhancement (increase in the metric for all except metric 4) over all the cases for which the LCB was best. This was done for LCB relative to each of the other 3 configurations.

Metric 1	LCB over LC	17%
	LCB over EXT	46%
	LCB over BASE	8%
Metric 2	LCB over LC	4%
	LCB over EXT	11%
	LCB over BASE	14%
Metric 3	LCB over LC	20%
	LCB over EXT	22%
	LCB over BASE	4%
Metric 4	LCB over LC	32%
	LCB over EXT	27%
	LCB over BASE	30%
Metric 5	LCB over LC	14%
	LCB over EXT	13%
	LCB over BASE	5%
Metric 6	LCB over LC	9%
	LCB over EXT	20%

Table 4.3 Average percentage of maneuverability enhancement due to LCB

Note that no comparison between LCB and BASE is possible for metric 6, since for the cases where LCB was highest in pitch acceleration the BASE configuration was not flown. Indeed, it may appear that, with the exception of metric 4 (maximum sideslip), the BASE configuration performed quite well versus the LCB based on this table. But recall that the AOAs tested for the BASE were 20 and 25 degrees, and only 6 cases of the 19 were so tested. Also, one might claim that the EXT performed comparably to the LC based on these numbers. But ALL departures seen were for the EXT configuration and it departed nearly 20% of the time.

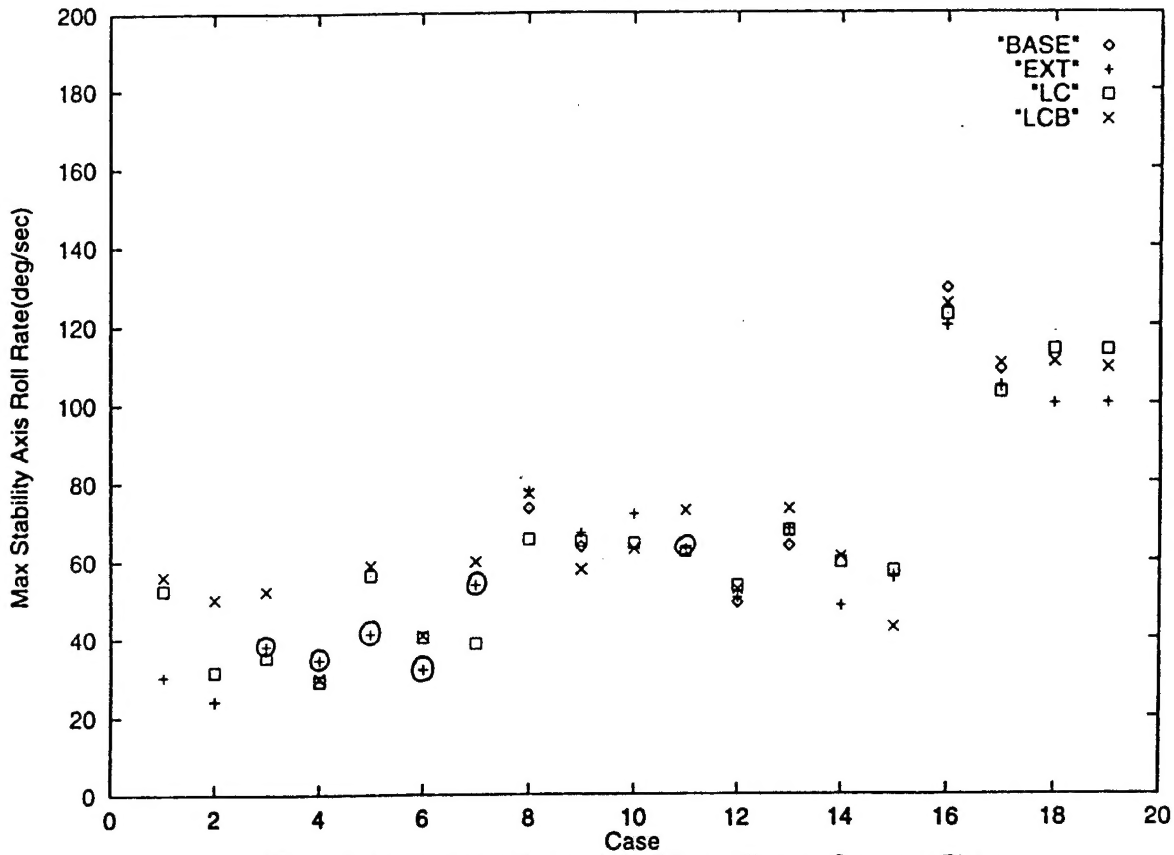

Figure 3 Metric1: Max Stab Axis Roll Rate: Pilot-avg Summary Plots

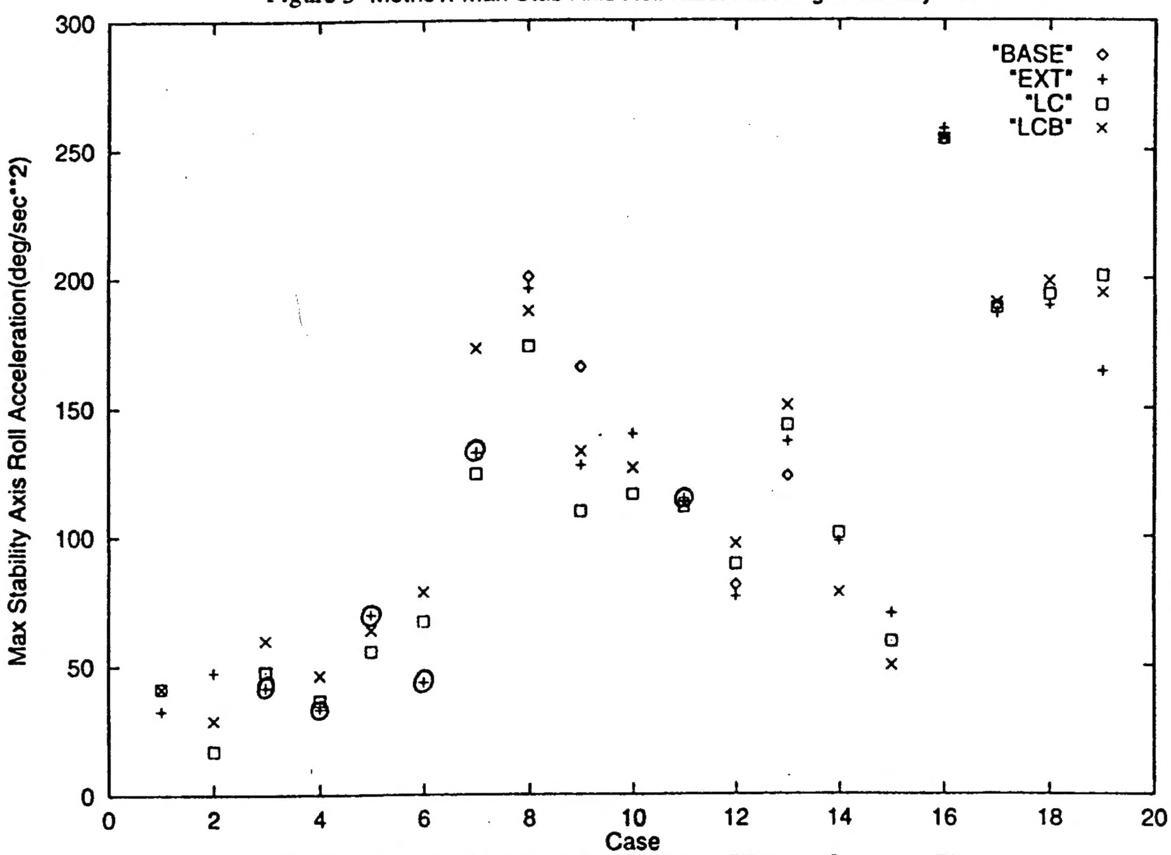

Figure 4 Metric2: Max Stab Axis Roll Acc: Pilot-avg Summary Plots

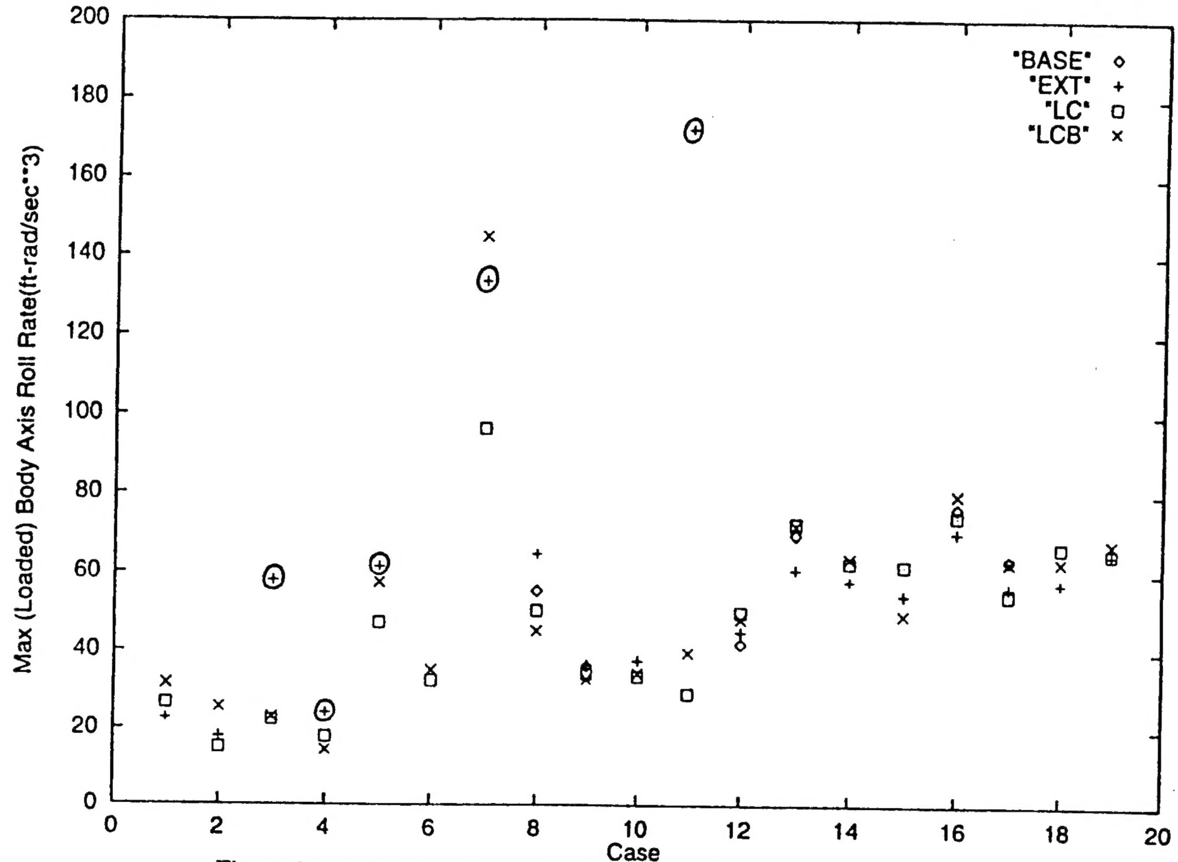

Figure 5 Metric3: Max (Loaded) Body Axis Roll Rate: Pilot-avg Summary Plots

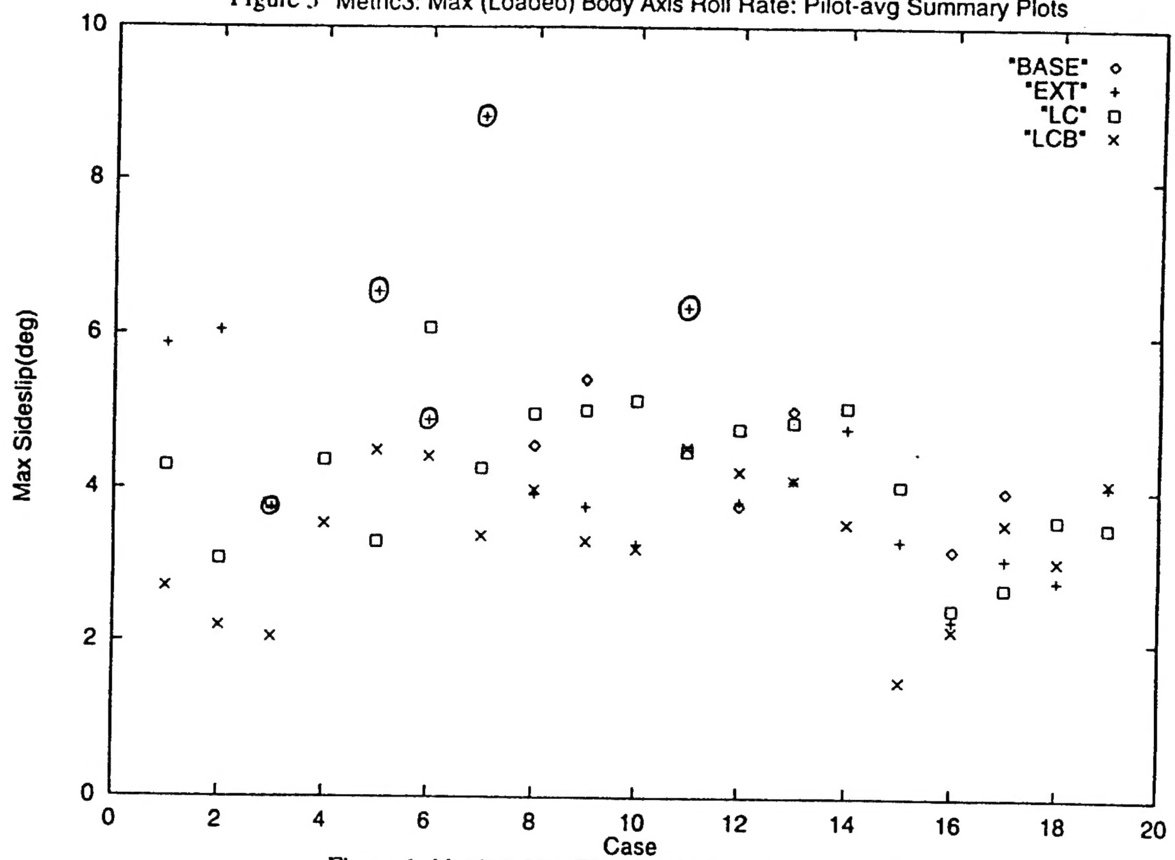

Figure 6 Metric4: Max Sideslip: Pilot-avg Summary Plots

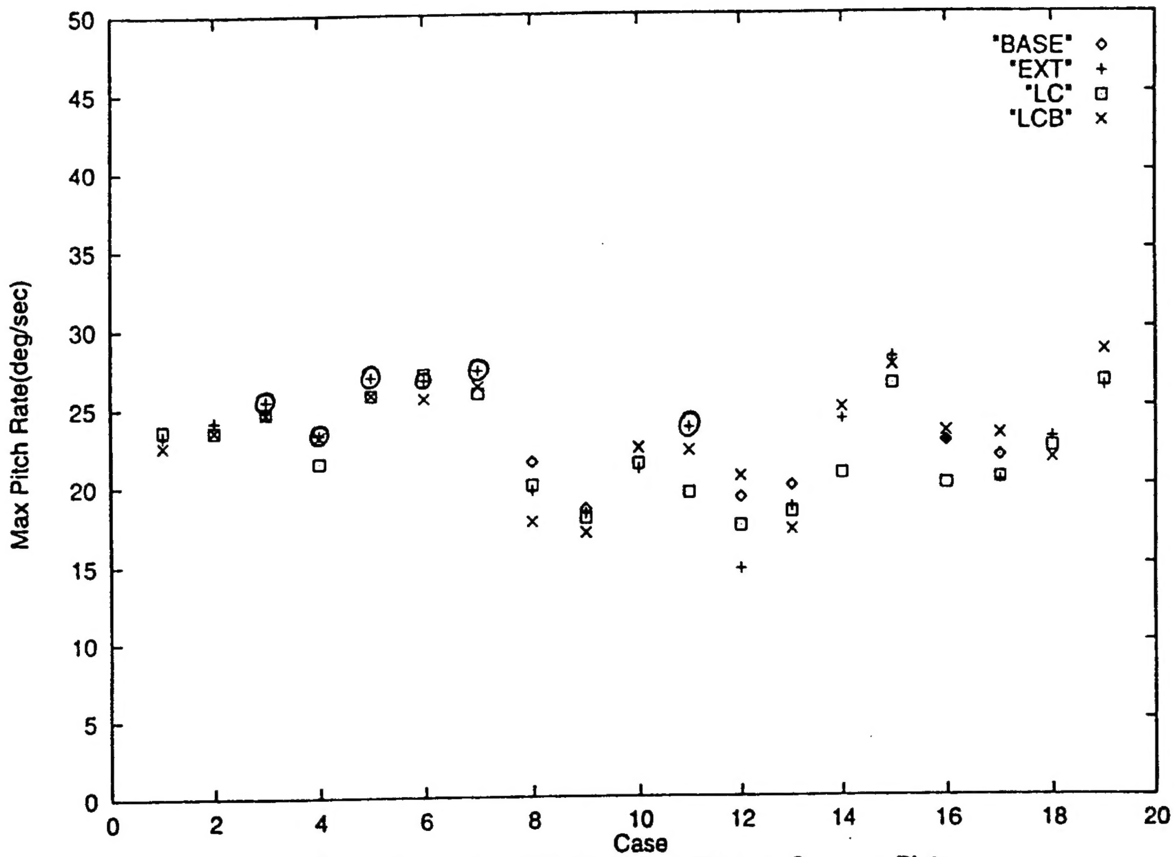

Figure 7 Metric5: Max Pitch Rate: Pilot-avg Summary Plots

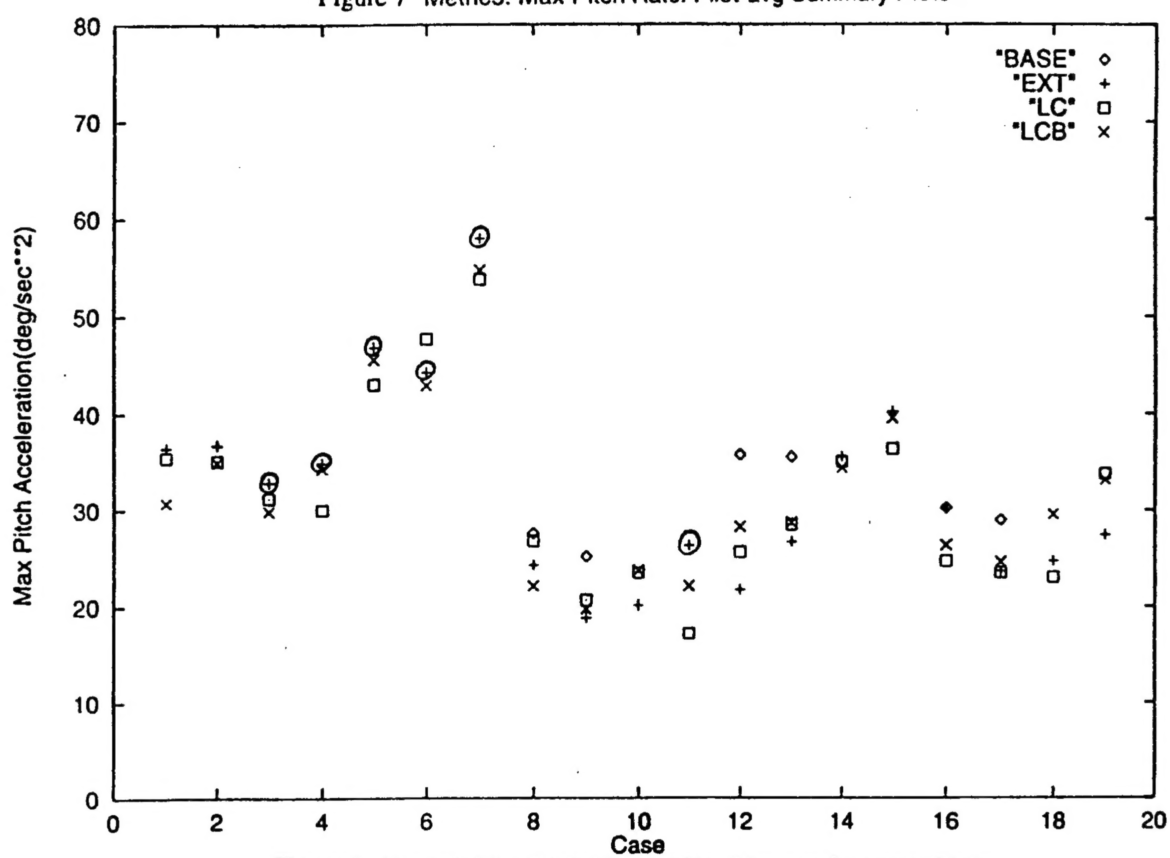

Figure 8 Metric6: Max Pitch Acceleration: Pilot-avg Summary Plots

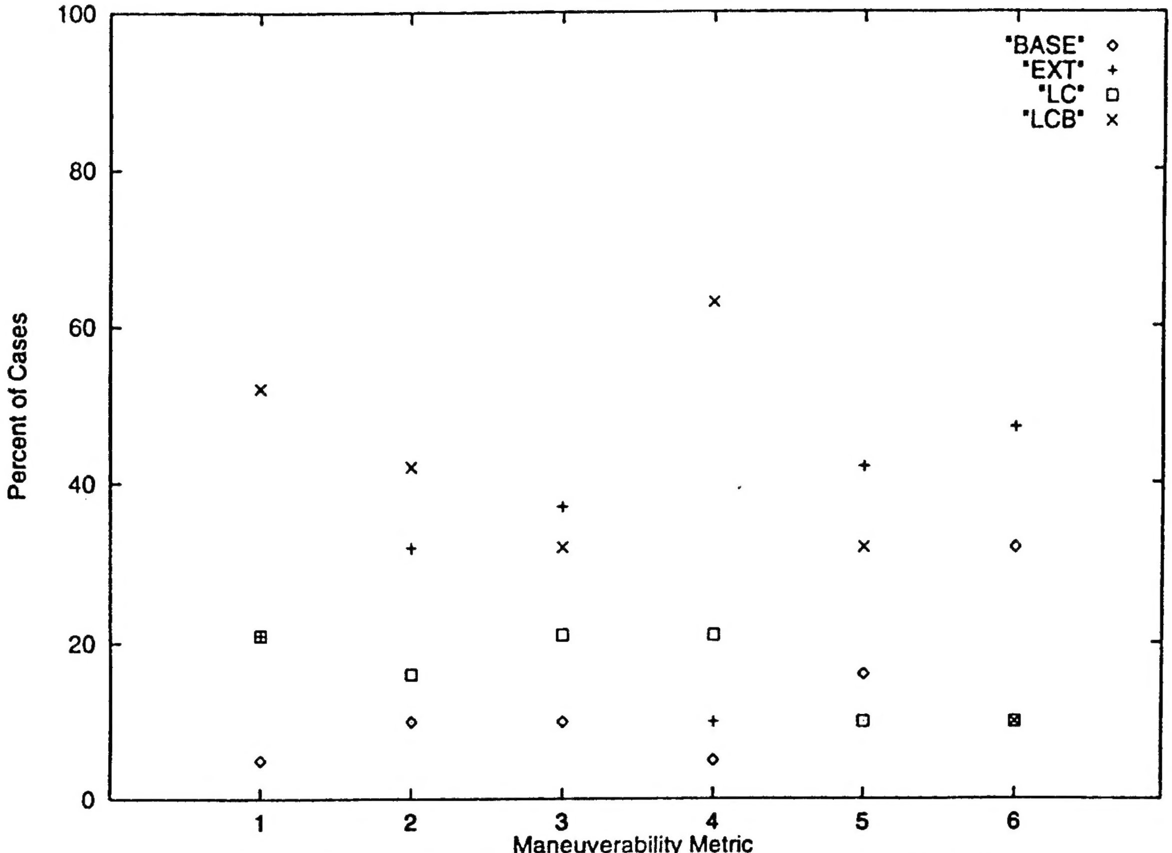

Figure 9 Pilot-avg: Percent of Cases With Best Maneuverability Metric Value

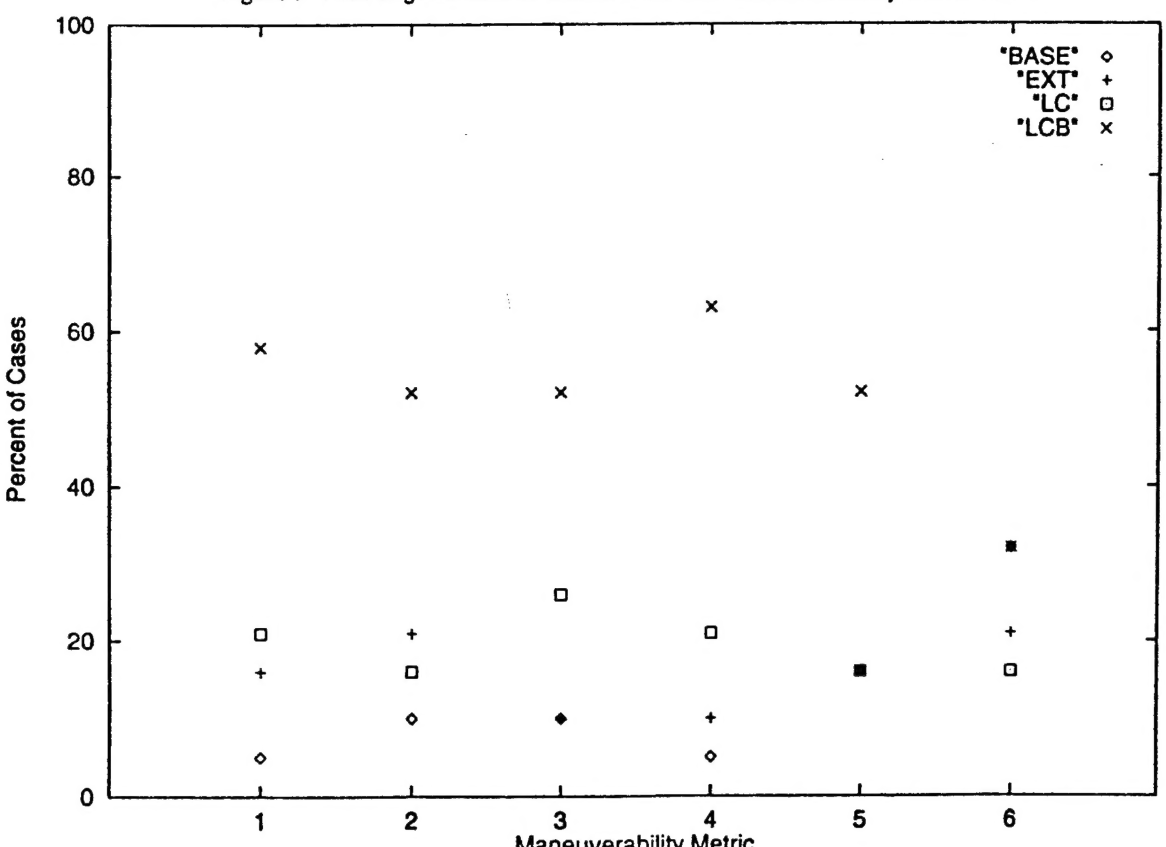

Figure 10 Pilot-avg: Percent of Cases With Best Maneuverability Metric Value(AFD)

CONCLUSIONS

Based on a thorough analysis of the simulation output data, the conclusion is that the use of all of these modifications allows for flight up to the maximum lift AOA(approximately 35 degrees) with greatly increased departure resistance compared to a VISTA without the modifications. Further, the modifications provide a significant (27%) improvement in sideslip attenuation over an unmodified VISTA flying at max lift AOA, and a significant (46%) improvement in roll maneuverability as measured by the maximum stability axis roll rate. The modifications produce pitch maneuverability at least comparable to an unmodified VISTA.

The issue of tactical utility improvements due to the modifications was outside the scope of the experiment. However, the results obtained concerning departure resistance and improved roll maneuverability at max lift AOAs suggest that such tactical utility improvements would be consistent with the results of this study. Further research and experimentation, including one-on-one piloted simulation combat scenarios between these 4 configurations, would be the next step in trying to determine possible tactical utility improvements due to these modifications. Following that, similar combat scenario simulations between this modified VISTA and the MATV could also prove to be very beneficial in determining the usefulness of forebody vortex control in air-to-air combat.

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